UNIVERSITI PUTRA MALAYSIA

PERFORMANCE EVALUATION OF ORTHOGONAL FREQUENCY DIVISION MULTIPLIXING SYSTEMS OVER INDOOR MULTIPATH FADING CHANNELS

MOHAMMED ABDO SAEED

PERFORMANCE EVALUATION OF ORTHOGONAL FREQUENCY DIVISION MULTIPLIXING SYSTEMS OVER INDOOR MULTIPATH FADING CHANNELS

BY

MOHAMMED ABDO SAEED

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Partial Requirements for the Degree of Master of Science

September 2003

To my parents and my wife

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the partial requirements for the degree of Master of Science

PERFORMANCE EVALUATION OF ORTHOGONAL FREQUENCY DIVISION MULTIPLIXING SYSTEMS OVER INDOOR MULTIPATH FADING CHANNELS

By

MOHAMMED ABDO SAEED

September 2003

Chairman: Professor Borhanuddin Mohd. Ali, Ph.D.

Faculty: Engineering

High-data-rate communications are limited not only by noise but often more significantly by the intersymbol interference (ISI) which arises due to the memory of the dispersive multipath fading channels.

The aim of this thesis is to investigate the performance of the Orthogonal Frequency Division Multiplexing (OFDM) scheme over wideband multipath fading channels. OFDM is a technique that can be used for transmitting data at extremely high rates by means of splitting up the serial data stream into several parallel streams which are transmitted simultaneously on different subcarriers, each occupying a small fraction of the available bandwidth. By inserting guard interval that is longer than the delay spread of the channel between the OFDM symbols, the ISI can be mitigated or totally eliminated.

In this thesis, the theoretical description and modeling of dispersive multipath fading channels is presented. A proposed channel model based on Saleh and Valenzuela model is introduced and implemented by computer simulation. The bit-error-rate (BER) performance of the uncoded OFDM system, in terms of energy per bit-to noise ratio (EBNR), is investigated by simulations for different modulation schemes with both coherent and differential detection. The influence of the number of carriers as well as the guard interval duration on the performance is also investigated.

We observed that the EBNR required to achieve a certain BER is significantly increased by 8 – 10 dB for dense multipath fading channels over that required in additive white Gaussian noise (AWGN) channels due to the decrease of the signal power as a result of increasing the number of paths. In addition, differential modulation improves performance in environments where rapid changes in phase are possible. OFDM can be implemented equally well with coherent (non-differential) modulation and demodulation to maximize the signal-to-noise ratio performance of the system. These performance measures are useful for the design and assessment of high speed indoor wireless communication systems.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi sebahagian keperluan untuk ijazah Master Sains

PENILAIAN PRESTASI SISTEM PEMULTIPLEKSAN PEMBAHAGIAN FREKUENSI ORTOGONAL DI DALAM SALURAN FADING PELBAGAI-LALUAN

Oleh

MOHAMMED ABDO SAEED

Mei 2003

Pengerusi: **Profesor Borhanuddin Mohd. Ali, Ph.D.**

Fakulti: **Kejuruteraan**

Komunikasi berkelajuan-tinggi dihadkan oleh bukan sahaja hingar tetapi lebih penting lagi Gangguan Antara-Simbol(ISI) yang berlaku disebabkan oleh kesan ingatan saluran fading pelbagai-laluan dispersif.

Tujuan tesis ini adalah penyelidikan prestasi skim Pemultipleksan Pembahagi Frekuensi Ortogonal(OFDM) ke atas saluran fading pelbagai-laluan jalurluas. OFDM adalah satu tekbik yang boleh digunakan untuk penghantaran data pada kelajuan yang terlampau tinggi melalui cara pemecahan aliran data selari kepada beberapa aliran siri yang dihantar secara sekaligus menggunakan sun-pembawa yang berlainan di mana setiap satunya menggunakan satu fraksi kecil lebarjalur yang ada. Melalui kaedah memasukkan jeda kawalan yang lebih panjang daripada sebaran lengahan saluran di antara simbol-simbol OFDM, ISI boleh dikurangkan atau dihapuskan semua sekali.

Dalam tesis ini, pencirian teoretikal dan pemodelan saluran fading pelbagai-laluan dispersif dipersembahkan menggunakan proses stokastik Gaussian tertib ke-dua. Satu cadangan model saluran yang berasaskan kepada model Saleh-dan-Valenzuela diperkenalkan dan dilaksanakan melalui simulasi komputer. Kadar ralat bit (BER) dikaji untuk skim pemodulatan yang berbeza dengan kedua-dua pengesanan kohiren dan diferenshil. Pengaruh bilangan pembawa dan juga tempoh jeda kawalan ke atas prestasi juga diselidiki.

Kami membuat pemerhatian bahawa EBNR yang diperlukan untuk mencapai BER tertentu bertambah begitu jelas sekali iaitu 8 hingga 10 dB untuk saluran fading pelbagai-laluan berbanding EBNR yang diperlukan untuk saluran hingar putih Gaussian aditif(AWGN) disebabkan pengurangan kuasa isyarat akibat daripada pertambahan bilangan laluan. Sebagai tambahan, pemodulatan diferenshil memperbaiki prestasi dalam suasana di mana perubahan cepat dalam fasa boleh terjadi. OFDM boleh dilaksanakan sama bagusnya dengan pemodulatan dan penyah-modulatan kohiren(bukan diferenshil) untuk memaksimakan prestasi nisbah isyarat-ke-hingar sistem tersebut. Parameter prestasi ini berguna untuk rekacipta dan penilaian sistem komunikasi wayarles dalam bangunan yang berkelajuan tinggi.

ACKNOWLEDGEMENTS

In the name of ALLAH, the Most Beneficent, the Most Merciful

First of all, I would like to express my greatest gratitude to ALLAH the almighty, for his help and support during the course of life and moment of truth. Alhamdulillah.

I would like to express my sincerely gratitude and deepest thanks to my supervisor, Professor Borhanuddin Mohd. Ali for his invaluable guidance, advice, support, and enthusiasm. His suggestions and encouragement was helpful during the course of the thesis work. He has always been willing to take time out of his hectic schedule to review the work and make corrections and improvements in the interim and final draft of this thesis. What I learn from him will provide me with lifetime benefits. He has always been a truly positive person.

My sincere appreciation goes to my advisory committee, Dr. Mohd. Hadi Habaebi, Dr. V. Prakash, and Puan Ratna Kalos for their advice, participating enthusiastically in the discussions, and comments on this work. Dr. Hadi has played an important role in motivating me and contributing critical suggestions throughout the progress of the thesis project.

I am grateful to the entire excellent group at the wireless laboratory in which I have found it really joyful to work.

To my wife, I would like to thank you for your support and encouragement during my studies and your enriching companionship through the years.

I certify that an Examination Committee met on 26 September 2003 to conduct the final examination of Mohammed Abdo Saeed Hezam on his Master of Science thesis entitled "Performance Evaluation of Orthogonal Frequency Division Multiplexing (OFDM) Systems in Indoor Multipath Fading Channels" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

ABDULRAHMAN RAMLI, Ph.D.
Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

BORHANUDDIN MOHD ALI, Ph.D.
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

MOHD HADI HABAEBI, Ph.D.
Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

RATNA KALOS
Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

GULAM RUSUL RAHMAT-ALI, Ph.D.
Professor/Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 04 DEC 2003

This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the partial requirements for the degree of Master of Science. The members of the Supervisory Committee are as follows:

BORHANUDDIN MOHD ALI, Ph.D.
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

MOHD HADI HABAEBI, Ph.D.
Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

RATNA KALOS
Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

AINI IDERIS, Ph.D.
Professor/Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 05 JAN 2004

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

MOHAMMED ABDO SAEED

Date: 19/05/2003

TABLE OF CONTENTS

LIST OF TABLES

Table

LIST OF FIGURES

LIST OF ABBREVIATIONS

16PSK	16-ary PSK
16QAM	16-ary QAM
2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project (for Europe and Asia)
3GPP2	Third Generation Partnership Project (for North America)
4G	Fourth Generation
A/D	Analog-to-Digital Converter
ACTS	Advanced Communications Technologies and Services
ADSL	Asynchronous Digital Subscriber Line
ATM	Asynchronous Transfer Mode
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary PSK
BRAN	Broadband Radio Access Networks
CDMA	Code Division Multiple Access
CIR	Channel Impulse Response
D/A	Digital-to-Analog Converter
DAB	Digital Audio Broadcast
D-AMPS	Digital Advanced Mobile Phone Services
dB	deciBel
DC	Direct Current
DFT	Discrete Fourier Transform
DMT	Discrete Multitone
DVB	Digital Video Broadcast
EBNR	Energy per Bit-to-Noise Ratio
ETSI	European telecommunication Standardization Institute
FDM	Frequency Division Multiplexing
FFT	Fast Fourier Transform
FM	Frequency Modulation
GSM	Global System for Mobile communications
HDSL	High-bit-rate DSL
HDTV	High Definition Television
HIPERLAN	High PErformance LAN
ICI	Intercarrier interference
IEEE 802.11	European ETSI HIPERLAN type 1 standard
IEEE P802.15	IEEE Project for WPANS
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse FFT
IMT-2000	International Mobile Telecommunications-2000
IP	Internet Protocol
IQ	In-phase and Quadrature-phase
IrDA	Infrared Data Association

IS-95	Interim Standard 95
ISI	Intersymbol Interference
LAN	Local Area Network
LOS	Line-Of-Sight
MDPSK	M-ary Differential Phase-Shift Keying
OFDM	Orthogonal Frequency Division Multiplexing
PAPR	Peak-to-Average Power Ratio
PDC	Pacific Digital Cellular
PDP	Power Delay Profile
PHY	Physical-layer
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature PSK
RCPCC	Rate-Compatible Punctured Convolutional Coding
RF	Radio Frequency
rms	root mean square
RS	Reed–Solomon Codes
SNR	Signal-to-Noise Ratio
S-V	Saleh-Valenzuela
TDMA	Time Division Multiple Access
UHF	Ultra High Frequency
UMTS	Universal Mobile Telecommunications System
US	Uncorrelated Scattering
UWB	Ultra-Wideband
VDSL	Very high-speed Digital Subscriber Lines
VoIP	Voice over IP
WAND	Wireless ATM Network Demonstrator
WATM	Wireless Asynchronous Transfer Mode
W-CDMA	Wideband-CDMA system
W-LANs	Wireless Local Area Networks
WPANs	Wireless Personal Area Networks
WSS	Wide-Sense Stationary
WSSUS	Wide-Sense Stationary Uncorrelated Scattering

CHAPTER 1

INTRODUCTION

In the past few years, wireless digital communications and Internet have seen an explosive growth both in their technologies and in their subscribers. The expected convergence of mobile telephony, Internet access, portable computing, and potentially many multimedia applications such as video and high quality audio has created a new paradigm of research and development efforts that enables multimedia content to move seamlessly between the Internet and mobile wireless networks. This resulted in an increased demand for new methods of obtaining wireless networks with high capacity and more flexibility.

Although second generation (2G) cellular communication systems which consists of the first mobile digital communication systems such as the Time Division Multiple Access (TDMA) based Global System for Mobile communications (GSM), Digital Advanced Mobile Phone Services (D-AMPS), Pacific Digital Cellular (PDC) and the Code Division Multiple Access (CDMA) based system (IS-95) provide mainly voice telephony and simple paging services, they are limited by very low bit transmission rates (9.6 kbps to 14.4 kbps) and incompatible global standards, and are not suitable to provide Internet and other multimedia services [1]-[3].

On the other hand, the emerging "Third Generation" (3G) mobile communication systems, called International Mobile Telecommunications-2000 (IMT-2000) or

Universal Mobile Telecommunications System (UMTS), uses Wideband-CDMA system (W-CDMA) and the CDMA-2000 system, are currently being deployed to meet the required higher data rates than 2G systems, supporting data rates from 64 kbps (vehicle speeds) to 384 kbps (walking), and eventually up to 2 Mbps for local coverage (indoor fixed applications) and at least 144 kbps for wide-area coverage (vehicular) [1]. The higher data rate of 3G systems will be able to support a wide range of services and multimedia applications including voice communications, mobile videophones and fast Internet access. In addition, new kinds of services could be supported, such as universal personal numbering, satellite telephony, wireless appliances, wireless web cameras, notebooks with built-in mobile phones, car navigation systems, and so forth. But most of these services will be limited by the cost of the service.

The deployment of 3G systems started in Japan in 2001, and during the past three years several licenses have been awarded to operators in Europe to deploy the technology and it is expected that the first services are available at the end of 2003 in some countries like Sweden. However, the encountered problems with the technology and network roll out costs are forcing operators to delay services launch. However, the network providers in Europe and North America currently maintain separate standard bodies (3GPP for Europe and Asia; 3GPP2 for North America). This reflects differences in air interface technologies. These technological and financial issues cast a shadow over 3G's desirability.

While the rolling-out of 3G systems is under progress, research activities on the 'Fourth Generation" (4G) mobile communication systems have already started. The commercial rollout of these systems is likely to be within 5-10 years from now, and will replace the current proliferation of core cellular networks with a single worldwide cellular core network standard based on IP for control, video, packet data, and VoIP [4]. For the time being, there is no clear vision which ingredients will define this future system generation. However, based on the developing trends of mobile communications, we can say that 4G systems will be to extend the capabilities of 3G systems, and they will have broader bandwidth, higher data rate, high capacity, smoother and quicker handoff, wider mobile area, more services, low cost per bit, IP-based services, etc. Certainly, transmission rates will be further increased over that of 3G to provide greater than 20 Mbps. 4G systems will again follow the migratory path and will evolve to a fully integrated network based on "all IP Network" concept. On the horizon is a 4th-generation wireless network that will allow broadband wireless access (in the order of 100 Mbps) to an all-IP backbone network and QoS support for multimedia applications. However, in order to cover these applications, the service cost must be reduced significantly comparing with that of 3G networks. Therefore, one challenging issue of the 4G systems is to significantly improve the spectral efficiency in order to be able to support high data rate services at low cost [5][6].

At the same time, there has been an increasing interest in high-speed Wireless Local Area Networks (W-LANs) [7], and new standards for short-range wireless technology such as Bluetooth and infrared transmission (IrDA) are rapidly enabling a plethora of novel applications in viable computing and personal-area networking. The W-LANs systems do not offer the same wide area coverage as the third generation mobile systems do, but within their limited coverage area they provide much higher data rates. They currently use the IEEE802.11b standard, which provides a maximum data rate of 11 Mbps [7][8]. On the other hand, W-LAN standards based on the IEEE 802.11a in the USA [9], and ETSI High Performance Local Area Network type 2 (HIPERLAN/2) in Europe [10], are based on Orthogonal Frequency Division Multiplexing (OFDM) technology and will allow broadband wireless multimedia and data communication in the office and home with much higher data rate up to 54 Mbps. Additionally, OFDM is being considered for future broadband applications such as wireless Asynchronous Transfer Mode ATM and fourth generation transmission techniques [11]. So there is a need for further improve the spectral efficiency and data capacity of OFDM systems to cope with W-LAN applications in the next generation.

1.1 Multicarrier Modulation

One of the challenging problems in the design of digital communication systems is how to choose the modulation scheme in order to get robust and efficient systems. This choice is greatly affected by the environment in which the system is supposed to work. For mobile or wireless applications, the channel is often described as a set of independent multipath components. Therefore, the delay and the expected received power for each component are among the most important parameters when choosing the modulation scheme. Large delays for strong paths mean that the interference between the different received symbols can be severe, especially when the symbol rate is high.

In a traditional communication system, the information to be transmitted is modulated onto a single carrier, so a single fade or interferer can cause the entire link to fail. To obtain high bit rates, the symbols have to be transmitted fast and thereby they occupy the entire bandwidth. When the channel is frequency selective, consecutive symbols will interfere with each other causing what is called intersymbol interference (ISI), a major problem in wideband transmission over multipath fading channels, which make it harder to recognize the transmitted symbol, and thereby causes severe degradation of the system performance.

There are many methods proposed to combat the ISI [12]. Multicarrier modulation techniques, including Orthogonal Frequency Division Multiplex (OFDM), are among the more promising solutions to this problem [13]. In multicarrier, a single datastream is transmitted in parallel over a number of lower rate subcarriers by splitting the available bandwidth into several orthogonal overlapping subchannels. Thus, fading will affect only a small percentage of the subcarriers. Error correction coding can then be used to correct for the few erroneous subcarriers. In the frequency domain, each subchannel will occupy only a small frequency interval where the channel frequency response will be almost constant and each symbol will hence experience an approximately flat fading channel. By using orthogonal subcarriers, the interchannel interference (ICI) will be eliminated, and the symbols transmitted on the different subchannels will not interfere.

1.2 Orthogonal Frequency Division Multiplexing

In communication systems, to increase the information transfer speed, the time for each transmission necessarily becomes shorter. Since the delay time caused by multipath remains constant, ISI becomes a limitation in high-data-rate communication [14]. Orthogonal Frequency Division Multiplexing (OFDM) avoids this problem by sending many low speed transmissions simultaneously. OFDM is one of the most attractive multicarrier modulation schemes for high bandwidth efficiency and strong immunity to multipath fading. It allows digital data at extremely high rates to be reliably and efficiently transmitted over a radio channel, even in multipath mobile environments. The use of fast Fourier transform (FFT) algorithms eliminates arrays of sinusoidal generators and makes the implementation of the technology cost-effective. In this technique, the high-rate serial data stream is split into a number of parallel data streams at a much lower symbol rate, which are modulated on a set of narrow bandwidth subcarriers [12][13]. The idea is to make the symbol period long with respect to the channel impulse response in order to reduce ISI.

Parallel transmitting of the subcarriers (for example N_{sc}) results in symbol duration of N_{sc} times as long as compared with a single carrier transmission, so strong immunity to multipath fading is achieved. The construction of an OFDM signal with five subcarriers is shown in Figure 1.1. All subcarriers have the same phase and amplitude, but in practice the amplitudes and phases may be modulated differently for each subcarrier. Note that each subcarrier has exactly an integer number of cycles over the symbol interval, and the number of cycles between adjacent subcarriers differs by exactly one, to account for the orthogonality between the subcarriers. High spectral efficiency is achieved by arranging the subcarriers in a manner that the sidebands of the individual subcarriers overlap and the signals are still received without adjacent carrier interference (see Figure 1.2b). Inter-carrier-interference (ICI) is avoided due to the orthogonality.

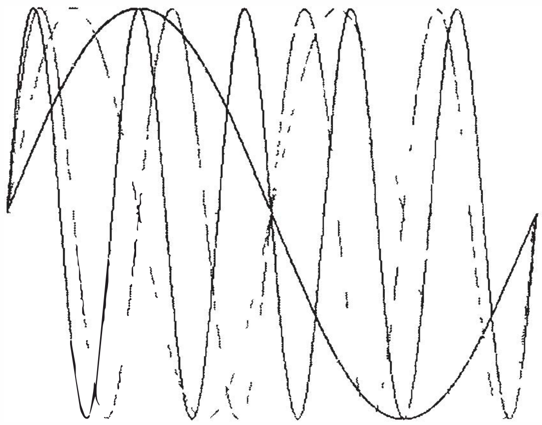

Figure 1.1: Example of five subcarriers within one OFDM symbol

The receiver acts as a bank of demodulators, translating each carrier down to DC, with the resulting signal integrated over a symbol period to recover the raw data. If the other carriers all beat down the frequencies that, in the time domain, have a whole number of cycles in the symbol period T_s, then the integration process results in zero contribution from all these other carriers. Thus, the carriers are orthogonal if the carrier spacing is a multiple of $1/T_s$. Figure 1.2(a) shows the spectrum of the individual data of the subchannel, while Figure 1.2(b) illustrates that at the center frequency of each subcarrier, there is no cross talks from other subchannels. Therefore, if we use discrete Fourier transform DFT at the receiver and calculate correlation values with the center of frequency of each subcarrier, we recover the transmitted data with no cross talk

The major drawback of OFDM system is its large peak-to-average power ratio (PAPR). A large PAPR corresponds to a high probability of the OFDM signal being clipped when passing through a power amplifier at the end of the transmitter. Clipping reduces the